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GPC-enhanced read-out of holograms

Mark Villangca*, Andrew Bañas, Darwin Palima, Jesper Glückstad

DTU Fotonik, Department of Photonics Engineering, Oersteds Plads 343, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

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ABSTRACT

The Generalized Phase Contrast (GPC) method has been demonstrated to reshape light efficiently to match the input beam profile requirement of different illumination targets. A spatially coherent beam can be GPC-shaped into a variety of static and dynamic profiles to match e.g. fixed commercially available modulation systems or for more irregular and dynamic shapes such as found in advanced optogenetic light-excitations of neurons. In this work, we integrate a static GPC light shaper to illuminate a phase-only spatial light modulator encoding dynamic phase holograms. The GPC-enhanced phase-holograms are encoded to create reconfigurable spot arrays and arbitrary extended patterns. For a given laser power, our experimental results show a significant intensity gain in the resulting diffraction patterns when we illuminate the holograms with a GPC-shaped beam as compared to the more common practice of hard truncation. The phase flatness of the GPC-enhanced readout beam has also been investigated.

1. Introduction

Our ability to efficiently shape light has paved the way for a host of important progress in photonics and biological research. Starting from the pioneering work of Ashkin on radiation forces [1], we have seen improvements on dynamic multiparticle optical trapping primarily using diffractive beam shaping techniques such as computer generated holography. Holography allows efficient control of light by controlling the amplitude, phase or both, giving rise to holographic optical tweezers (HOT) [2,3] which has become an important tool in biology. An extension of the HOT is the creation of optical landscapes for more complex optical traps [4] and induced effects such as orbital angular momentum [5]. Recently, the use of simultaneous multi-site two-photon photolysis to uncage neurotransmitters using holographic projection of multiple focal spots has been reported [6]. The use of multiple intense focal spots using diffractive optical elements [7] and microlens arrays [8] has unique applications in two-photon polymerization of multiple structures in parallel.

In all these applications, the need for high light throughput is desirable. Moreover, it is also desirable to illuminate beam shaping devices, such as spatial light modulators (SLMs), with a uniform beam that matches the profile of the modulation element. Uniform illumination is crucial when directly imaging the SLM pattern, e.g. patterned light projections using digital micromirror devices (DMDs) to maintain consistency across the projected field. Although, in principle, one can directly use a Gaussian laser beam to efficiently illuminate phase holograms, this can be problematic when using liquid crystal-based devices (e.g., LCoS) for high power applications due to the intensity hotspot at the center of the beam and the broadened point spread function. In this case, uniform illumination presents a practical solution by spreading the incident power to achieve higher power throughput within the power limits of the device.

The most common method for illuminating beam shaping devices – expanding and truncating the laser beam – wastes photons and achieves uniform illumination by sacrificing light efficiency. Yet, many beam shaping applications demand high efficiency. In the work by Kato et al. on multi-spot parallel microfabrication [8], they needed to amplify the laser source to address a fixed microlens array. In this case the available laser power limits the extent to which processes can be parallelized. Since energy is distributed among the focal spots, increasing the number of focal spots creates spots with lower intensities. This problem is compounded for applications based on two-photon excitation, which depend quadratically on intensity [9]. These power considerations may be mitigated, if one can afford higher power sources (although commercial availability may be difficult for some wavelengths). Nevertheless, efficient energy usage is always desirable and should always be encouraged in any optical engineering design. More recently, the feasibility of a 2000-fold parallelized dual color STED fluorescence nanoscopy has been reported [10]. The lateral resolution of STED nanoscopy is dependent on intensity and therefore such massive parallelization would require high intensity input pulse. In this case, "the STED pulse energy is a

* Corresponding author.
E-mail address: jesper.gluckstad@fotonik.dtu.dk (J. Glückstad).
URL: http://www.ppo.dk (M. Villangca).

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limiting factor to achieve highest resolution and large super-resolved fields of view at the same time" [10]. The Gaussian envelope of STED intensity makes the resolution position dependent that varies according to square root law. This particular application highlights the need for high input power and uniform illumination. Given the above constraints, it is therefore necessary to have an efficient photon management system that reshapes light by utilizing as much photons from available laser sources.

In this work, we propose to uniformly illuminate and match the profile of beam shaping elements and yet maintain high light efficiency by using the GPC method to create an efficient static input beam shaping prior to intended dynamic beam modulation applications. The GPC method provides a straightforward phase to intensity mapping using a simple 4*f* imaging setup and can be considered as a generalization of Zernike's phase contrast microscopy technique applied to beam shaping and optical information processing [11]. GPC has been used to generate speckle-free extended light patterns and has recently been combined with temporal focusing in rapidly reconfigurable two-photon optogenetics to create neuron-shaped excitations [12]. Prior theoretical and numerical predictions has been carried out to optimize and match GPC light shaping for Gaussian laser profiles [13,14]. Although GPC can be directly used for beam shaping in various applications it can also help researchers that use other beam shaping methods by improving light efficiency in their applications. The current work examines this hybrid implementation where the GPC method is used to pre-shape the input beam for optimal illumination of any type of dynamic modulation element. For illustration, we demonstrate illumination of a spatial light modulator (SLM) encoded with dynamic computer generated holograms. The SLM has been chosen for this experiment due to its wide range of use in optical trapping, microfabrication and photo-excitation. The performance of the GPC-enhanced approach is compared to the traditional case of a hard-truncated input beam for the same input laser power. Reconfigurable spot arrays and extended light patterns serve as intensity targets.

2. Methodology

2.1. Creating optimal illumination with a GPC light shaper module

The GPC method uses a 4*f* imaging configuration to perform a robust common-path phase-to-intensity mapping as shown in Fig. 1. The incident Gaussian beam passes through a phase mask that introduces a π phase shift within a defined region. For our purpose we use a phase mask that has a rectangular phase shifting region matching the geometry of the SLM used in the diffractive setup. A lens focuses the beam through a phase contrast filter (PCF) which π-phase-shifts spatial frequencies around the zero-order. A second lens transforms these phase-shifted components

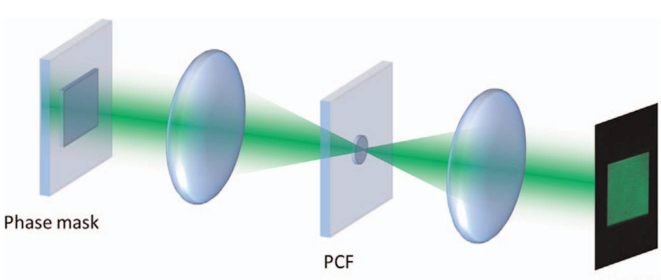

Fig. 1. Schematic diagram of the GPC light shaper module. The static phase mask has a rectangular phase shifting region with a 4:3 aspect ratio to match the area of SLM encoding phase holograms.

forming a so-called synthetic reference wave (SRW) at the output of the 4*f* system. The SRW and the unperturbed copy of the input then interfere at the output plane creating an intensity distribution corresponding to the static phase mask pattern. This creates an intense beam that matches the shape of the phase-only modulation element (SLM) in the diffractive setup. For the experiment, we combine elements of the GPC in a compact add-on module, called the GPC Light Shaper (LS) [16], that can be conveniently integrated to an existing holographic setup.

We use a GPC LS designed for $\lambda_0 = 532$ nm wavelength and beam diameter $2w_0 = 1$ mm. A rectangular phase mask with 4:3 aspect ratio is used to match the SLM. The rectangular phase mask has a width of $W = 2\zeta w_0 = 408.7\ \mu$m and a height of $H = \frac{3}{4}W = 306.5\ \mu$m. The radius of the PCF is given by $\Delta f_r = \eta w_f = 18.76\ \mu$m. The parameter ζ represents the ratio of the phase mask radius and the input beam waist, w_0, while η is the ratio of the PCF radius and the focal plane beam waist, w_f. For the above calculations, we used the values $\zeta = 0.4087$ and $\eta = 1.1081$ which are optimized for contrast and efficiency [15]. A numerical analysis for a circular phase mask across different eta and zeta shows that the acceptable input beam waist can be up to 2.5 times the phase mask radius provided the corresponding PCF is comparable to the beam waist of the focused Gaussian beam at the PCF plane [13]. The limitation on the achievable PCF size is determined by the smallest feature size that can be etched and the damage threshold of the material used since a large input beam would result in a small intense focal spot. Error tolerance calculation for the GPC LS used in the experiment indicate that the system can tolerate axial misalignments within 2% of the focal length of the lens used and lateral displacements within 20% of the PCF radius and still maintain above 80% of is peak operating efficiency [16].

2.2. Optimally illuminating a digital holography setup

For an illustrative SLM-based beam shaping application, we used a diffractive optical setup in an optical Fourier transform geometry, as shown in Fig. 2, which consists of a diode-pumped solid-state laser (Laser Quantum Excel, $\lambda_0 = 532$ nm) with beam diameter $2w_0 = 1.5$ mm. The horizontally polarized laser beam is de-magnified (1/1.5 times) to meet the specifications of the fixed GPC light shaper module which generates a small rectangular output beam profile with a 4:3 aspect ratio. The beam is magnified before passing through a rectangular iris which blocks peripheral light, also allowing direct comparison with a hard-truncated Gaussian. The resulting rectangular beam is then projected to a phase-only spatial light modulator (Hamamatsu Photonics, 792×600 pixels, 9.9 mm $\times$ 7.5 mm active area) to read out holographic phase patterns encoded on the SLM. The modulated beam is Fourier transformed using a lens ($f = 250$ mm) and subsequently imaged to a beam profiler (Gentec-EO, Beamage 3.0).

For the hard-truncated input beam, the phase mask and phase contrast filter (PCF) are retained but the PCF is slightly displaced to move the phase shifting region away from the beam path and disable the phase contrast effect. This ensures that the input beam encounters the same perturbations along the optical beam path to the SLM and onwards. During comparison of the GPC-enhanced and hard-truncated hologram read outs, laser power is kept constant. Hence, any improvement is attributed to the beam shaping involved prior to the phase modulation at the SLM.

3. Experiments with multiple light spots and extended light patterns

The output intensity profiles of the GPC LS and hard truncation

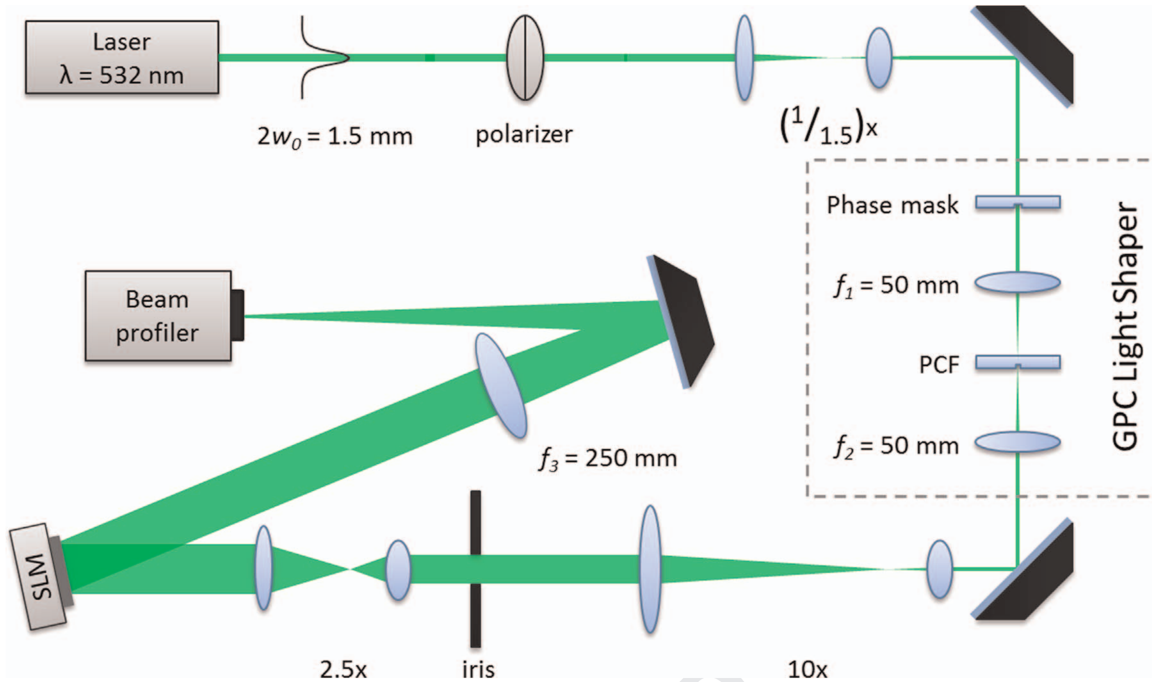

Fig. 2. Diffractive phase-only modulation setup. A GPC light shaper module is added for efficient illumination of the phase modulation element (i.e. SLM).

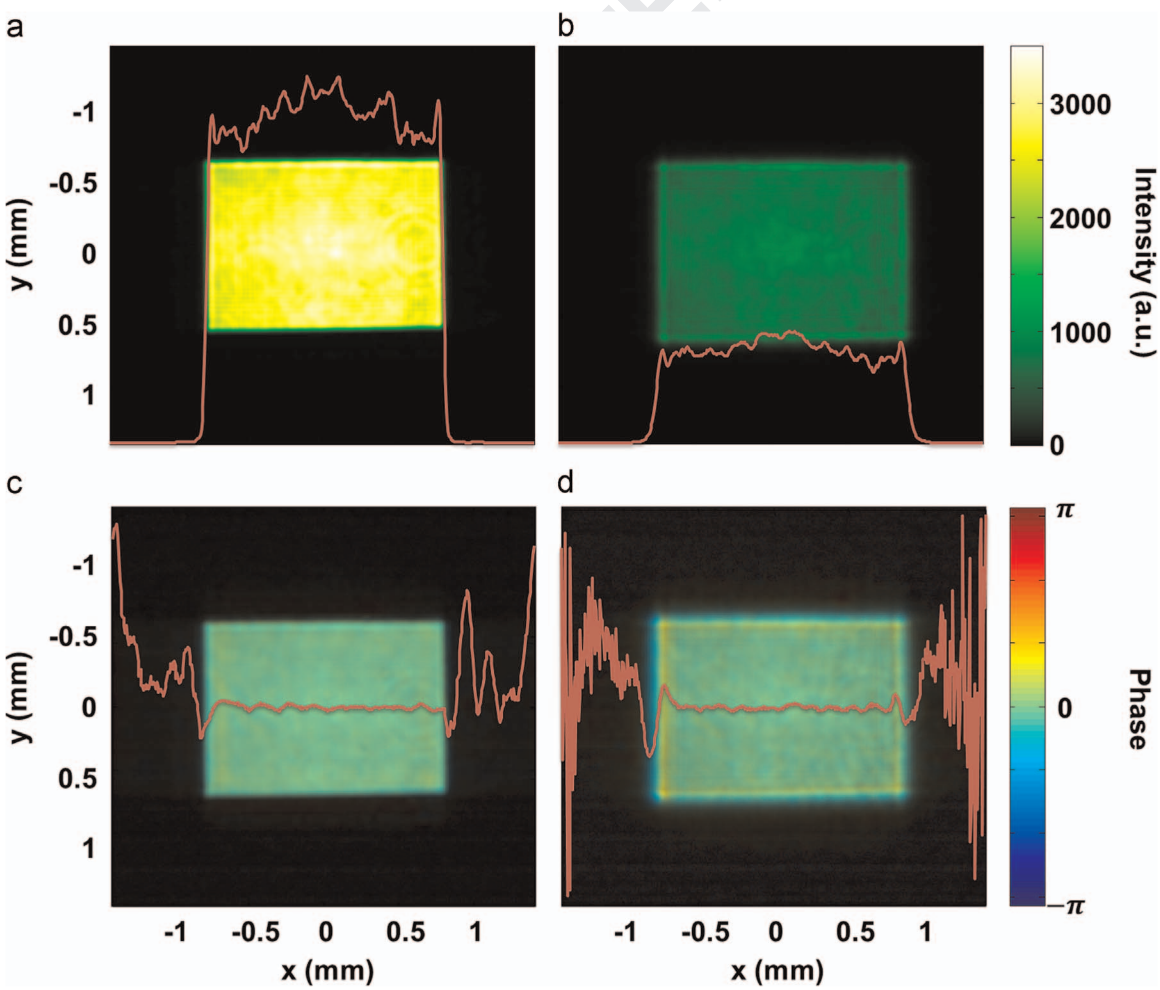

Fig. 3. Comparison of the output intensity profile for (a) GPC-shaped and (b) hard-truncated beams. (c) and (d) show the phase profiles of the GPC-shaped and hard-truncated beams respectively. The intensity values from (a) and (b) are used as brightness values for the color mapping to highlight the regions of interest respectively. Outside the region of interest, there are rapid phase fluctuations due to dark noise in the beam profiler. The red line plot are line scans of intensity and phase taken at $y = 0$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are shown for comparison in Fig. 3. Both exhibit a relatively flat profile but there is considerable intensity increase of about 3 times for the GPC-shaped beam. When illuminating phase-modulating elements, the phase uniformity of the illuminating beam is crucial to avoid distorting the final reconstructions (or encoding matching corrections, if possible). The phases for both beams shown in Fig. 3 were calculated using a multiple plane iterative phase retrieval based on the Gerchberg–Saxton algorithm [17]. Four images separated by 1 mm are taken by imaging the beam emerging from the iris to the beam profiler. These intensity images serve as amplitude constraints in the calculation. The normalized mean square errors for the iterative calculations are below 0.002. Within the high intensity region, the phase is flat for both beam shaping modalities. Abrupt phase change happens at the edge of the rectangular intensity pattern. The line scans for the phase shows rapid fluctuations outside the region of interest due the dark noise from the beam profiler, but this is not critical for the application.

Typical applications of diffractive phase modulation are for light-efficient dynamic spot generation in optical tweezers or, more recently, for uncaging neurotransmitters and optogenetic photoexcitation in neurophotonics research. Hence, we first tested the GPC light shaper in a dynamic spot-projecting holographic configuration. We performed a modified Gerchberg–Saxton algorithm [17,18] to compute the phase pattern necessary for generating a random arrangement of light spots. We have, however, not optimized the phase to produce patterns with a reduced zero-order and/or higher-order spurious diffraction. Holographic projections were demonstrated for both GPC-shaped and for hard-truncated input beams. The images captured by the beam profiler are shown in Fig. 4 where we used the built-in despeckle filter of the included software. The GPC-enhanced spots are more intense than their hard-truncated counterparts and do not exhibit any gross distortions, consistent with expectations from having a flat illumination phase determined earlier. The intensity gain is quantified using the ratio of the average light spot intensity in the GPC-enhanced pattern to the corresponding average light spot intensity in hard-truncated case (the zero order diffraction is not included in the calculation).

Both the GPC-enhanced and hard-truncated readout beams have flat phase making them suitable for phase modulation

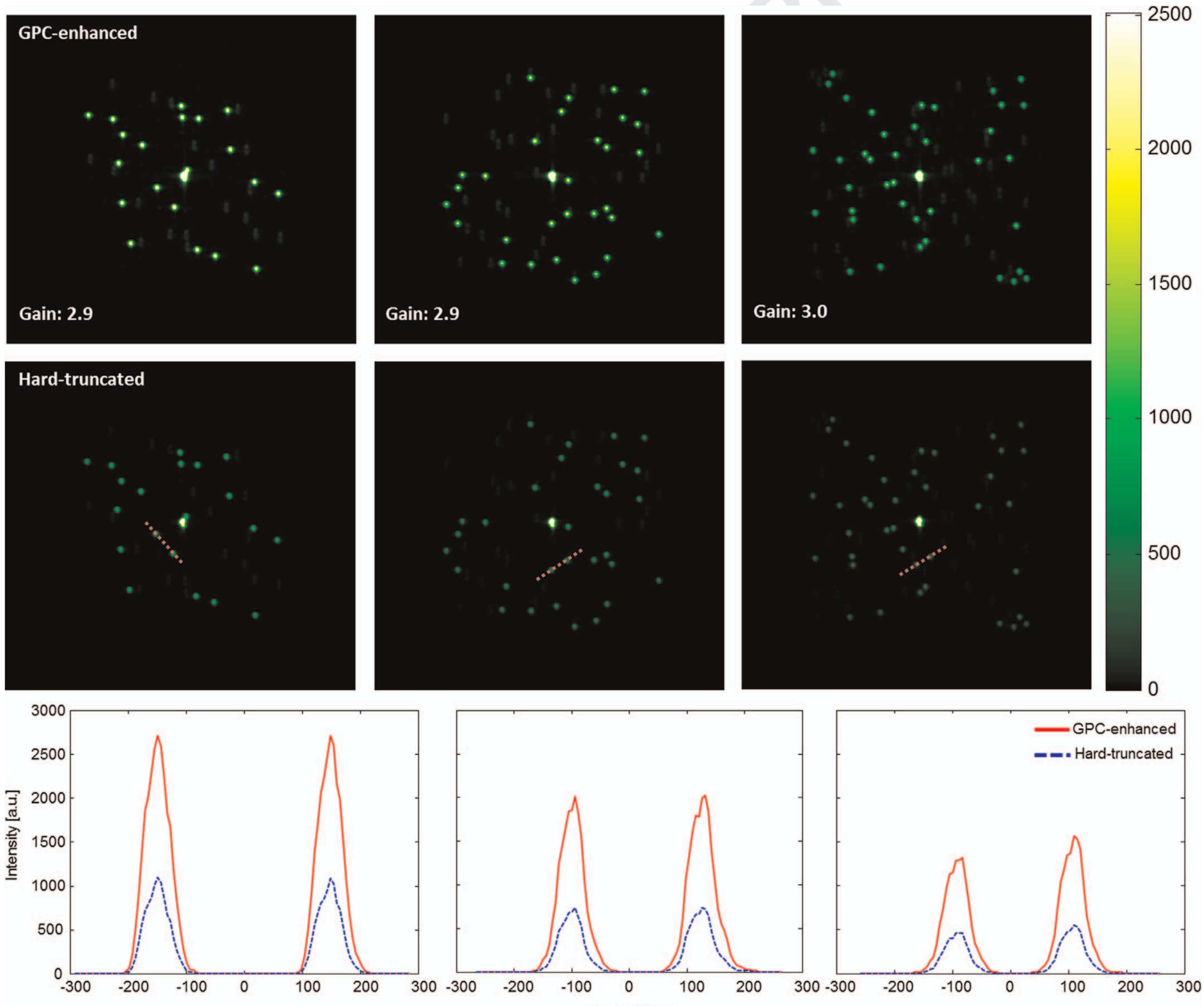

Fig. 4. Diffraction patterns for 20, 30 and 40 light spots. The bright spot in the middle of each image is the zero-order diffraction. We show line scans, indicated by the dotted line in the captured images, to compare the peaks.

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applications. However, the high intensity gain from the GPC-enhanced beam has major advantage for many applications. Fig. 4 clearly shows a significant increase in the intensity of the generated spot arrays when using GPC-enhanced readout. The $\sim 3\times$ gain means that three times more intense spots can be holographically generated with a GPC-enhanced readout using the same incident laser power. Alternatively, this enables a user to generate an array with $3\times$ more spots having the same intensities as the fewer spots when reading out by a hard-truncated beam. For example, the 40 spots created by GPC-enhanced readout in Fig. 4 are still brighter than the 20 spots in the hard-truncated case. This new functionality could have a large impact for various applications, e.g. requiring multiple optical tweezers [3], multi-site two-photon photolysis [6] and in parallel two-photon polymerization [8].

Another typical holographic application is the generation of arbitrary extended intensity patterns. However, the inherent presence of speckles is one major drawback of this beam shaping technique. A major cause of speckles in diffractively-generated extended light patterns is the "randomly" oscillating phase distribution at the far-field reconstruction plane mainly caused by cross-talk between adjacent output resolution elements due to the optical convolution process with the point spread function (PSF) of the system [19,20]. Considering that we get 4:3 rectangular output with both GPC LS and hard truncation, the PSF for both will have a 2D sinc profile matching the 4:3 aspect ratio and the difference will only be by a scaling factor due to the gain in the GPC LS. Alternatively, the SLM can be illuminated directly with small Gaussian beam to fit inside the active phase modulation region. However, this comes at the expense of losing some of modulation pixels and consequently having a broader jinc PSF. Moreover, the central hotspot can be problematic for high power applications, as previously discussed in Section 1, which provides the motivation for using uniform illumination. Utilizing much of the SLM pixels is suggested for applications requiring finer resolutions and thus highlights the importance of a properly match readout beam.

For our extended pattern targets, we use the university's logo and a binarized version of a standard test image. Fig. 5 shows our results for extended light patterns and there is a substantial intensity gain in the resulting holographic reconstruction of extended intensity patterns similar to the spot arrays. The presence of speckle (not an effect by the GPC-enhanced read-out) is in general an undesirable feature of phase-only holography but for some applications this can be tolerated when the aim is to efficiently generate high intensities such as is the case for two-photon fabrication [21,22].

Complex beam shaping methods may be employed to reduce speckles however cascading SLMs or other pixel-based diffractive modulation element to address both amplitude and phase is inefficient due to the inherently low diffraction efficiency of SLMs and may demand high input powers for operation. Typical efficiency of the first diffraction order from a phase grating in an SLM is 41%.

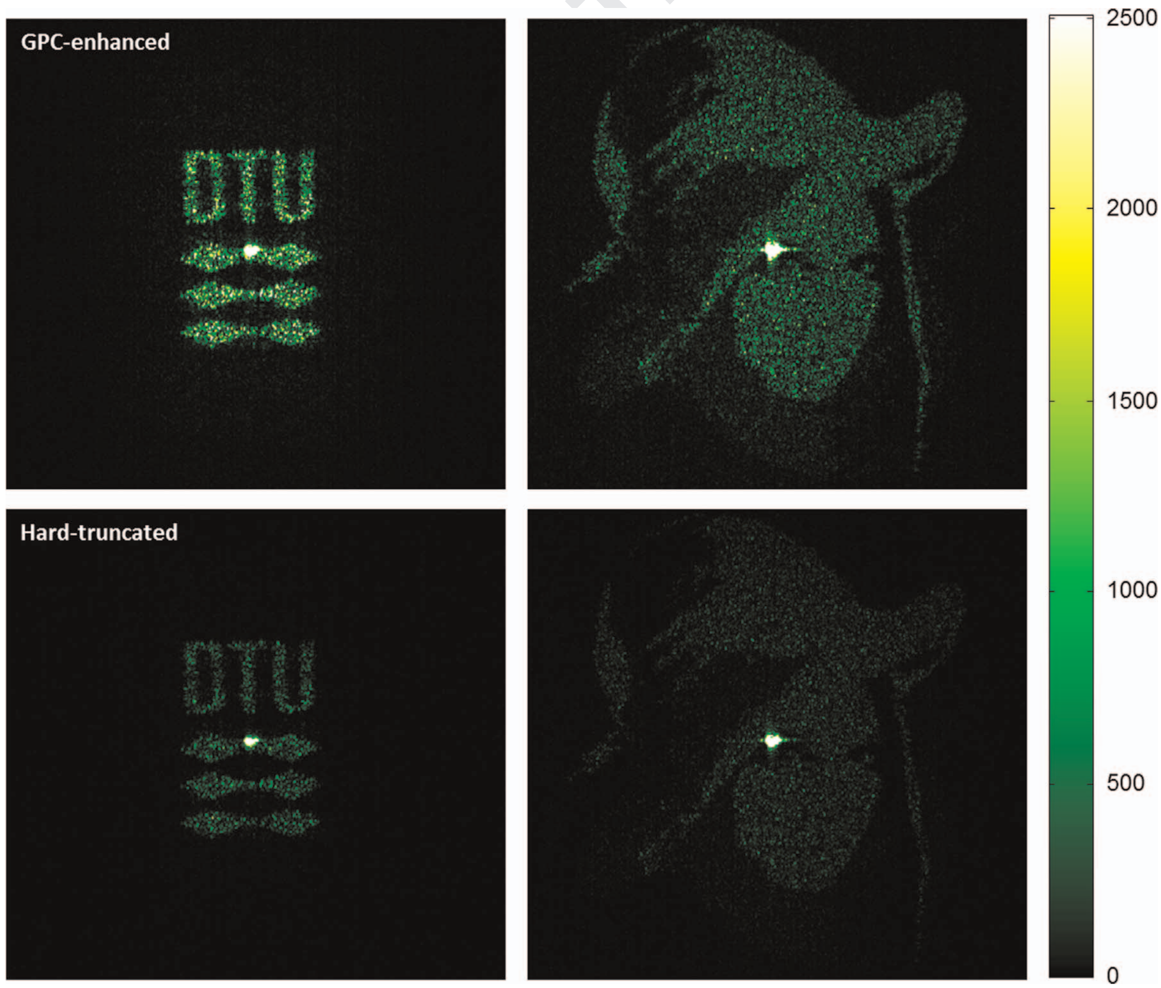

Fig. 5. Extended pattern projections using GPC-enhanced and hard-truncated read-out beams, respectively. Both cases exhibit identical speckle distributions but there is a noticeable gain in intensity for the GPC-enhanced case.

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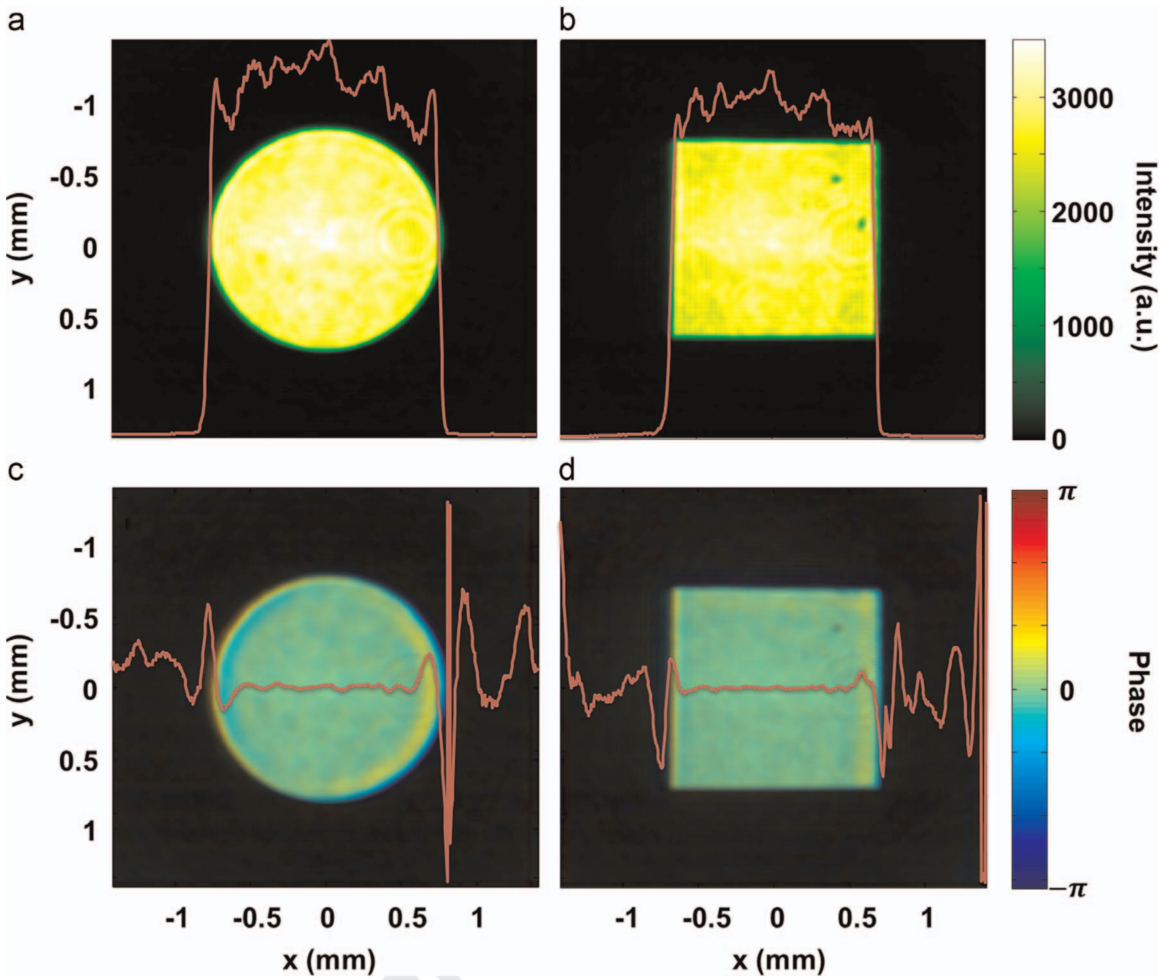

Fig. 6. The GPC LS can illuminate different devices by changing the phase mask such as (a) circle and (b) square. (c) and (d) show the respective phase profiles.

There are other applications where a circular input is desired such as in direct illumination of microscope objective for fixed beam optical trap. The GPC LS can also adapt a circular shape and other rectangular shapes by simply changing the phase mask. A commercial device known as πShaper also accomplishes this same task using a field mapping approach with a series of refractive elements [23]. The output of the πShaper has high efficiency and has a more flat profile although the output intensity profile is limited to patterns with circular symmetry and a square pattern [24]. The advantage of the GPC LS is that it can work with arbitrary phase mask shapes. The different phase masks and PCFs can then be fabricated *en masse* in single fused silica wafer with a standard chemical wet etching process. This makes the GPC LS more economical and moving from different devices is just a matter of changing the appropriate phase mask. Some of the intensity patterns that can be projected using the GPC LS are shown in Fig. 6. The GPC LS has also been shown to work with a wide range of wavelength in the range $[0.75\lambda_0,\ 1.5\lambda_0]$ [25].

4. Conclusion

We have presented a light-efficient method of reading out a phase-only spatial light modulator using the Generalized Phase Contrast method as a compact add-on module called the GPC Light Shaper. The method utilizes as many photons as possible in a given laser power setting creating a high intensity output that matches the shape of the modulating device. The flat output phase makes it suitable for illuminating phase-only spatial light modulators. We have shown the ability to create trapping spots or diffractive light patterns that are about 3 times more intense than using the traditional approach of hard-truncation. Alternatively, this means we only need 1/3 of the laser power to create similar intensity-level patterns to the hard-truncated case or 3 times more trapping spots or diffractive pattern fill factor.

The above conclusion can be appreciated better when one considers a scenario where a given laser source is already operating at its maximum output and yet still not sufficient to perform, for example, a holographic multi-beam trapping experiment of colloidal particles. The use of the GPC LS prior to holographic encoding is able to “squeeze out” 3 times more photons compared to the simple hard truncation. This gain in photons might just allow an experimentalist to carry out this trapping experiment with the given maximum power at hand. This scenario can be extended to application cases that aim to parallelize processes based on focused light by producing multiple foci.

The method presented here can be advantageous for a host of photonic applications such as multiple optical tweezers, multi-site photolysis in neurophotonics and parallel two-photon polymerization. Moreover, multiple plane beam shaping techniques can benefit from this enhanced read-out since the static beam shaping using the GPC LS is independent of the reconfigurable SLM phase encoding. Due to the versatility of the input phase masks for the GPC LS, the system is not limited to just simple rectangular or circular apertures of basic light modulating elements. For example, the phase masks used in the GPC light shaper can also be fabricated for systems requiring a light-efficient read-out of e.g. a microlens array or photonic devices with inherent specifically shaped active modulating elements.

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